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A Brief 50-Year Summary of Over-The Horizon H.F. Radar Effort of the Naval Research Laboratory

[Unclassified Title]

F. MALCOLM GAGER

Radar Division

October 1973

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TABLE OF CONTENTS

ABSTRACT
(Unclassified)

The U. S. Naval Research Laboratory is commemorating fifty years of continuous activity as a scientific and technical service to the Navy and DOD. This report is a brief summary, interspersed with documentation by report numbers, of NRL over-the-horizon H.F. radar effort covering the period.

A BRIEF 50-YEAR SUMMARY OF OVER-THE-HORIZON H.F. RADAR EFFORT OF THE NAVAL RESEARCH LABORATORY

(Unclassified Title)

INTRODUCTION

(U) The first observation of the radar effect took place in 1922, during experiments conducted by Navy personnel Dr. A. H. Taylor and L. Young. While operating an experimental high-frequency transmitter-receiver system along a path which crossed the Potomac River, they noticed that passing ships interfered with reception. This interference provided the first indication that objects in the path of radio waves could block their transmission.

(U)About 1925 a new method of studying the characteristics of the ionosphere using H.F. pulses reflected from the ionosphere was employed. The heights of the layers were obtained through a measurement of transit time of the pulses over the path. This idea, attributed to Breit and Tuve of the Carnegie Institute, actively involved Messrs. L. A. Gebhard and L. Young of NRL. Gebhard was responsible for the transmitter, which was also actively used in H.F. communications experiments for Navy. Young developed the receiver and displays. This ionosphere sounding equipment was set up at NRL for initial observations. Means of generating short pulses were at first mechanical, afterwards a successful multivibrator was employed by Schrenk at the suggestion of Gebhard. Oscillograph recordings of received pulses reflected from the ionosphere with this equipment gave positive proof, for the first time, of the existence of the ionosphere layers. The first observations were made at NRL with 4200 kHz transmissions on 28 July 1925. This initial installation was used by NRL and the Carnegie Institute of Washington to study the radio transmission and reflection characteristics of the ionosphere relative to diurnal variations, the influence of magnetic disturbances and correlation with solar flares.

(U) Subsequently the receiving and display equipment were moved to the Carnegie Institute and the system was employed as a bistatic ionosphere sounder. The Carnegie Institute carried on an extensive program of ionosphere sounding employing NRL transmissions. The new method was disclosed at an URSI meeting and many other observers used it thereafter. Not much has changed, over the years, in this pioneering approach to sounding the ionosphere.

(U) During the period 1925-1928, the existence of "transmission zones" and "skip zones", other than the first zones, were recognized by NRL as second hop, third hop, etc. These successive refractions by the ionosphere demonstrated that "round-the-world" H.F. transmissions could be obtained by proper choice of operating frequency, time of day and season of the year.

(U) In 1926 round-the-world signals were established by encirclement of the globe not once but as many as three times on the same transmission, and in both directions. The reflections from earth or sea surfaces called "backsplash" at that time are currently referred to as "backscatter". The transit time of the "backsplash" provided range to the successive reflection surfaces. This H.F. phenomenon was later employed by H.F. over-the-horizon radar.

(U) About 1930 NRL's Hyland, studying H.F. direction finding for Navy was surprised to find identifiable doppler signals at 32.8 MHz in his receiver output caused by aircraft flying nearby. This discovery initiated a study of H.F. aircraft detection. The initial CW system was subsequently abandoned for a more promising pulse method. The first important pulses from aircraft targets were obtained at 28.6 MHz on 28 April 1936.

(U) In the late 30's, previous to WW II, NRL's R.M. Page and others built and installed on a U.S. Navy ship an operable meter wave radar providing detections in both range and bearing. The tremendous radar activity during WW II emphasized, for the most part, microwave techniques and many of these radars performed their mission in an excellent manner. There were some complaints in the U.S. Fleet, however, that more and more microwave radar provided less and less detection range for some units. Unintentional comparisons were noted in mixed fleet operations (USN/RCN and USN/RN) where the RN/RCN 44 and 88 MHz radar sets outperformed some microwave radars in detection range.

(U) After WW II, and throughout the 40's, 50's and 60's the Special Research Branch of Radio Division III, now the Radar Techniques Branch of the Radar Division, carried on two partially overlapping, but related, programs. One the propagation of electromagnetic waves in rocket propellant gases; the other H.F. meter wave, over-the-horizon radar. The extensive work on the propagation of electromagnetic waves in propellant gases, but not all, is set forth in NRL Bibliography No. 8, Parts 1 and 2. This background work was found to be valuable and basic ground work in postulating detection of ionized media with H.F. as well as understanding later H.F. radar returns from atomic explosions, aurora, meteors and missiles under thrust conditions.

THE MUSIC RADAR

(U) On or about 1949 Dr. R.M. Page and others recognized a compelling need for detection of aircraft and missiles at extremely long ranges. It was felt that microwave radar had pushed aside some unfinished business in meter wave, H.F. radar and it was time to explore the H.F. spectrum especially if new ideas were at hand. Dr. Page wrote a report on Storage Radar, NRL Report 3532. Shortly thereafter Dr. Page, E.N. Zettle, G.K. Jensen, J.E. McGeogh, C.L. Uniacke and F.M. Gager, after numerous component considerations, devised an H.F. radar embodying cross correlation, storage and bandwidth narrowing which, if successful, promised a block of system gain heretofore not realized.

(U) Doubting Thomases of the time said that both the target and the ionosphere medium would not cooperate at H.F. frequencies with the proposed new techniques to produce useful results for extreme range, over-the-horizon detection. Thus much preliminary work, hardware and target measurement characteristics, preceded the development of a radar employing active filters, storage mechanisms, narrow band filtering and cross correlation.

(U) Attacks on the target aspects were in two phases. First the spectral content of moving target doppler returns were examined with low power, CW radars operating at 480, 1000, 2927, 4999 and 9375 kHz on line-of-sight aircraft and five inch rockets. These measurements were most encouraging (NRL Report 4258). The second phase was a low power study, pulse-to-pulse correlation between transmitted and received target signals at operating frequencies of 415, 3320, 9379 and 23,900 kHz. Again with line-of-sight targets the correlation coefficient was found to be close to unity (NRL Reports 4611 and 4835). As for suspected ionosphere difficulties, an extremely important parallel investigation of the spectral spread of the backscatter via the ionosphere was carried out (NRL Report 4976). This work pinned down the narrow extent of the backscatter doppler, normally plus or minus two cycles from the carrier, and apparently diving steeply into the noise. This latter feature was encouraging, because it was felt that increased transmitter power would not appreciably increase the observed spectral spread of the backscatter such as to mask the doppler of moving targets of interest.

(U) After extensive investigation of moving target returns, ionosphere backscatter characteristics and transmitter and receiver hardware innovations (NRL Reports 5441, 5589, 4848, 4134, 5201, 5238, 4630, 5187, 5247, 5338 and 5399) a decision was made in 1954 (NRL Report 4400) to assemble an experimental H.F. radar with twenty seconds integration time. This radar was called the MUSIC radar for multiple storage, integration correlation (NRL Reports 5016 and 5324). With this radar backscatter and transmitted hum were filter eliminated and due to low power (2 kW 50 kW peak)

aircraft detections were limited to 180 nautical miles with a modest gain antenna. The MUSIC radar was initially employed and subsequently improved to study the backscatter spectrum, over-the-horizon radar range/ground range problems, as well as demonstrate active filter real time target acquisition, reed filter bank doppler indicators (NRL Report 5187) and long range, over-the-horizon detection of beacons aboard aircraft which provided the bandwidth of beacon returns via the ionosphere as well as multipath responses from the ionosphere.

(C) Very interesting targets of opportunity became available in 1957-1958. The MUSIC radar was the only available appropriate tool of the time and in 1957 this radar pioneered in the detection of atomic tests at Frenchman's Flats, Nevada as well as early 1958 detections of missile launchings from Cape Canaveral, Florida in the form of missile induced ionosphere disturbances. Some of this and following work is set forth in NRL Reports 5508, 5511, 5564, 5584 and 5585. The MUSIC radar was actively used up to about 1961 and, apart from previous details, it was also employed in LOS detection of chemical releases from Wallops Island rocket launches (NRL Memo Report 1176). While the MUSIC radar was experiencing extensive yeoman's service, overlapping activity in new forms of signal processing and more versatile radars took place.

THE LOW POWER MADRE RADAR

(C) In 1954 Dr. R.M. Page and S. George of NRL suggested a signal processing mechanism employing magnetic storage and time compression (NRL Report 4878). Although this approach was initially aimed at improving moving target doppler signal handling for the MUSIC radar, it became apparent, if successful, that it would enhance the performance of a high power, very long range ionosphere refraction radar. As stated previously, the latter was the ultimate goal of these undertakings and received much encouragement from the performance of the MUSIC radar. It was early noted that the large block of processing gain was a reality. Calculations by B. Navid, and later by I. Page, showed that with realizable powers (100 kW or so) and suitable high gain antennas (23-26 dB) one could expect aircraft and other target detections in the 1000-2000 mile range.

(U) NRL wrote their specification for the magnetic storage/time compression signal processor and General Electric, Syracuse was awarded a competitive bid in 1955 to produce the drum storage signal processor, Contract (Nonr 1771(00)). At first this signal processor was visualized as an adjunct to the MUSIC radar. As it progressed, and funds became available, it was divorced from the MUSIC radar. With other hardware, some produced by NRL or by outside contract on NRL specifications, this radar became known as the LOW POWER MADRE RADAR, Madre for magnetic drum radar equipment. This radar was placed in operation at NRL in the fall of 1958. Among other features of advanced design it provided a frequency range of 10 to 30 MHz.

The philosophy of the magnetic drum signal processor is described by NRL Report 4878; NRL Report 5023 includes the magnetic drum storage mechanism in a radar system.

(U) The performance of the LOW POWER MADRE RADAR was pioneering in radar hardware providing real time display by doppler/range of the spectral spread of the backscatter, missile launch returns from Cape Canaveral activity and, most important, superior multiple aircraft detections, LOS, out to 180 nautical miles. In addition, airborne beacons and ground based beacons were used with this radar to enhance early knowledge of long range detection with the MUSIC radar on such phenomena as spectral spread of beacon returns and ionosphere multipath problems.

THE HIGH POWER MADRE RADAR

(U) While the MUSIC radar was in use and the LOW POWER MADRE was under construction, the prospects and design of a very long range (1000-2000) nautical mile radar was undergoing money procurement exercises. During the latter part of this active period (1956-1958) and after three abortive attempts the money problems were relieved by DOD emergency funding to Navy with USAF committment on financial support over the ensuing years. Thus in 1958 RCA, by competitive bid on NRL specifications, contracted (Nonr 2803(00)X) to provide two high gain H.F. antennas, a 100 kW 4.6 MW peak, tunable power amplifier and subsequently a back-up magnetic drum memory system. With the LOW POWER MADRE radar as the driver to this equipment, the whole, subsequently called the HIGH POWER MADRE RADAR, was installed at NRL's Chesapeake Bay Annex (now CBD), Bldg. 4. NRL Reports 5903 and 5875 provide some details.

(S) During the summer and fall of 1961 the HIGH POWER MADRE RADAR was activated. There were numerous pioneering, real time detection firsts with this radar. These include: long range (400-2400 nautical mile) detection of single and multiple aircraft over water and land (NRL Reports 6272, 5862, 5898, 5991, 6019, 6371, 6508, 7044, 7336); detection of missile launches from Cape Canaveral/Kennedy (NRL Reports 5825, 5881, 6238, 6485 and Memo Report 1251); detection of missile launches from Vandenberg AFB westbound (NRL Reports 5811, 5825, and Memo Reports 1287 and 1316); missile launches out of Green River, Utah for White Sands, N.M., including reentry phenomena at White Sands (NRL Report 6507 and Memo Report 1939); missile launches at White Sands (NRL Memo Report 1939); atomic tests (NRL Report 5962); H.F. radar cross section of the moon (Journal of Geophysical Research 69 No. 15, Radio Science 69D No. 2 '65, and NRL Report 5968); advanced H.F. propagation prediction analysis (NRL Reports 7336, 6590 and Memo Reports 1811, 1885, 2226 and 2500); railroad/highway traffic; sea state and storm center detection including coast line locations (NRL Report 7456 and 53rd Annual Meeting American Meteorological Society, 1 Feb. '73);

studies of antenna vertical patterns by meteor returns and rocket launches (NRL Report 6015); artificial ionosphere (chemical releases from Wallop's Island rocket shots - NRL Reports 5824 and 7059) including detection of aircraft over-the-horizon by such means; detection of very low flying aircraft (NRL Report 6508); ship detection (1968) and remote sensing aircraft fleet warning (NRL Reports 7350, 7500 and Proceedings Tri Service Symposium 17/18/19 June '69); long range detection of ionosphere heating (Boulder transmitters produced local ionosphere heating and the target effect was detected at NRL's CBD site. When the transmitters were shut down the target effect disappeared almost immediately whereas the flutter died out with time) and manned space flight launches and Atlantic Ocean reentry (NRL Report 6507).

(U) The HIGH POWER MADRE RADAR, still in operation at this writing, has been upgraded by many hardware improvements since the initial operation in 1961. Gas discharge T/R switches were found to be most unsatisfactory in life and recovery time at high power and the problem was solved by new and novel solid state switching (NRL Report 6198). NRL has stressed, at all times, achieving very high dynamic range in receivers and signal processors and high spectral purity of transmissions. The 30 dB dynamic range of the G.E. and RCA magnetic drum memories was superseded by a G.E. built 65 dB dynamic range digital core storage system which in turn was improved to 72 dB dynamic range.

(U) A range gated doppler time format displays moderate accelerations. If accelerations are severe (missiles) insufficient energy may be placed in many velocity bins and the target thereby lost unless acceleration processing is more sophisticated. Since 1958 NRL has concentrated on real time display of advanced signal processing of both radial velocity and acceleration in the form of doppler range, doppler time at gated ranges and acceleration vs range, time, velocity, etc., including some three dimensional displays. Such a velocity/acceleration processor with 100 dB dynamic range was developed (NRL Reports 6611 and 6992). Approach-recede target separation circuitry (NRL Report 6079) and contiguous filtering (NRL Report 6479) facilities have enhanced the real time display of events. A frequency programmer and selector built on NRL specifications by Sylvania Electronics Systems-East (Sylvania #11-1005-0811-002 14 July '64) was used extensively to study the H.F. band occupancy problems and availability of "clear" channels ("Some Skywave Radar Constraints" ARPA Meeting 17/18 May '67; "H.F. Interference/Noise" ARPA Meeting 23/25 Oct. '68; and "H.F. Interference Environment Analysis" ARPA Meeting 11/12 Dec. '69).

(S) With dynamic range capability in excess of 65 dB backscatter comb filtering usually becomes unnecessary. In this manner the entire doppler spectrum is displayable and the detection of very slow radial velocity targets (aircraft, ships and helicopters) is made possible. A most

interesting observation is the doppler return from helicopter blades, even if the helicopter is hovering or resting on a pad. This is a form of beacon response for very slow targets buried in the backscatter (NRL Report 7500).

(S) At this writing NRL's pioneering ground wave efforts at H.F. are several years old. Experiments have been made to detect aircraft and ships, line-of-sight and over-the-horizon, both monostatically and bistatically. Monostatic operations have been accomplished on the Chesapeake Bay with the high power MADRE equipment running at low power using special vertical antennas as well as loops in array for reception. Ship and aircraft returns as well as returns from approaching and receding wave structures are shown clearly as doppler amplitude spikes or as lines in doppler time at gated ranges. Slow radial velocity targets have been tracked both inside and outside the approach/recede wave returns and if a target coincides with a wave spike a slight shift in operating frequency produces separation ("H.F. Radar as a Fleet Sensor" NRL Technical Memo J.M. Headrick and D.C. Rohlfs 4 Aug. '69; "ARPA Proceedings of OHD Technical Review Meeting 17/18 March '71" and "Fifth Tri Service Symposium, Page 389, 1969").

(C) Wind direction sensing was first noticed in the H.F. ground wave experiments and this finding was applied to a previously mentioned work or storm center locations at great distances (NRL Report 7456). The bistatic tests were accomplished by using transmissions from Boulder, Colorado illuminating the MADRE site at CBD. With MADRE's superior receiving and signal processing equipment, nearby targets were detected (NRL Memo Report 2135). Improvements in this form of operation have been implemented by an array of receiving loops. In this manner the direction of the target as well as range from the receiving site can be determined.

(C) The NRL high power Madre radar contains captive computer means for operation flexibility, digital filtering and signal processing. Computer programs have been developed to take multiple aircraft detections as a function of time and compose time-range tracks of the individual targets (ARPA Proceedings 2/3 May '73). Important advances have also been made in ionosphere ray tracing by computer means as an important assist in operating frequency management (NRL Reports 6960, 7164, 7336 , 6731, 6866 and "Some Environmental Aspects of OTH Radar" page 362 and "NRL Skywave/ Surface Wave Radar" page 389 of Fifth Annual Tri Service Symposium 1967).

(S) The voluminous background of H.F. radar accomplishments by NRL are felt to be of operational use for the Navy. NRL Memo Report 2424 entitled "Naval Applications of Over-the-Horizon Radar," is an effort to set forth the various options and costs for several applications. The pioneering H.F. radar results from the Music radar, the low power Madre radar and the high power Madre radar, including the many hardware innovations, have

produced a cadre of specialists acting as consultants to DOD/USN/USAF interests in CONUS and other applications of over-the-horizon H.F. radar. The H.F. means are attractive in the protection of large land masses or task forces from surprise attack by long range bombers, missile - ICBM, IRBM, including sub launched and ship or aircraft launched missiles.

ACKNOWLEDGMENT

(U) Without mental reservation, the author extends extreme credit to all personnel of the Radar Techniques Branch of the Radar Division as well as those formerly of the Special Research Branch of Radio Division III, for their inventive skills, ingenuity and meticulous investigatory perseverence in making a joy out of pushing back the unknown walls of science and in an exemplary manner enlarging the known sphere.

BIBLIOGRAPHY STATEMENT

(U) There are approximately eighty NRL reports, seventy seven NRL Memo reports and forty five miscellaneous bibliography items, excluding technical memoranda and limited edition papers, which have been issued by NRL in the field of Over-the-Horizon radar. The bibliography submitted with this report is limited to the reports cited therein.

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13. ABSTRACT

The U.S. Naval Research Laboratory is commemorating fifty years of continuous activity as a scientific and technical service to the Navy and DOD. This report is a brief summary, interspersed with documentation by report numbers, of NRL over-the-horizon H. F. radar effort covering the period.

14. KEY WORDS	LINK A		LINK B		LINK C	
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Radar						
Radar history						
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